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RESEARCH ARTICLE

Coastal Vulnerability Assessment To Tidal (*Rob*) Flooding In Indramayu Coast, West Java, Indonesia

Sepanie Putiamini[1], Mufti Petala Patria[2], Tri Edhi Boedi Soesilo[3] and Asep Karsidi[4]
[1]School of Environmental Sciences, Universitas Indonesia, Salemba Raya Street No. 4, Central Jakarta,10430, Indonesia; National Research and Innovation Agency, B.J. Habibie Building, Jl. M.H. Thamrin No. 8, Central Jakarta,10430, Indonesia
[2]Faculty of Mathematics and Natural Science, Universitas Indonesia, UI collage Depok, West Java 16424, Indonesia
[3]School of Environmental Sciences, Universitas Indonesia, salemba Raya street no. 4, Central Jakarta,10430, Indonesia
[4]School of Environmental Sciences, Universitas Indonesia, salemba Raya street no. 4, Central Jakarta,10430, Indonesia

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Correspondent email: panieeputiamini@gmail.com

Abstract Aquaculture practices in developing countries, particularly Indonesia, are currently operating without effective control measures, leading to high tidal and other climate-related issues. Therefore, this study aimed to modify Coastal Vulnerability Index (CVI) assessment to evaluate the physical vulnerability of coastal areas in Indramayu Regency, West Java (62 sections) to tidal flooding (Rob). A total of 6 primary characteristics, including geomorphology, beach slope, water level rise sea, coastline alterations, tidal range, and high tide, as well as 2 additional parameters, namely land cover and mangrove breadth, were used for analysis. Based on the evaluation, CVI was divided into four groups, including (1) low, (2) moderate, (3) high, and (4) very high. The results showed that Indramayu District struggled to recover from tidal flooding, with 24.56%, 22.13%, 41.03%, and 12.28% being placed in the very high, high, moderate, and low categories. This underscored the role of local governments in improving coastal communities' capacity to respond to tidal flooding disasters. Furthermore, the results were expected to be used by local governments to enhance disaster mitigation systems, particularly for coastal areas in developing nations with comparable ecological conditions.

1. Introduction

Tidal flooding (Rob) and inundation are the major causes of the most knancially burdensome flooding in recorded history. The occurrence of these conditions has been reported to vary due to weather changes and ocean circulation patterns, including El Nino Southern Oscillation (ENSO) and mangrove degradation (Nurhidayah & McIlgorm, 2019; Coppenolle & Temmerman, 2020; Sweet et al., 2022). Furthermore, a previous study stated that annual climate-related disasters, particularly flooding and hurricanes, affected over two billion people, leading to 124,088 mortalities (Wallemacq et al., 2018). Indonesia is a developing country with several coastal areas and has been reported to be susceptible to various climate-related disasters. A total of 60% of the population in the country lives along the 100,000 km coastline, while 22% relies on kshing, causing high vulnerability to coastal risk. This high vulnerability can be attributed to the reliance on kshery and aquaculture resources for food, livelihood, and household income (Organisation for Economic Co-operation and Development, and the Food and Agricultural Organization,, 2017; Economic and Social Commission for Asia and the Pacikc, 2019). In the absence of effective adaptations, over 4.2 million people are projected to inhabit permanently flooding areas between 2070–2100, leading to economic loss in coastal agriculture (Suroso & Firman, 2018; Mohd et al., 2019; Syam et al., 2021).

According to previous reports, there are 13 districts along the coast of Java, Indonesia, which are known to experience recurrent coastal inundation flooding risk due to high tides commonly known as "Rob" in Javanese. These areas were subjected to simulation in this study by forcing tide elevations at open borders, as well as considering winds and temperatures (Nirwansyah & Braun, 2019; Septriayadi & Hamhaber, 2013; Andreas et al., 2017; Suroso & Firman, 2018). Furthermore, a quantitative evaluation of the physical vulnerability (to tidal flooding) of 5 sub-districts in Indramayu coastal area (up to 6.12 km in length) was carried out, as shown in Figure 1. Indramayu District serves as a tangible example, showing the applicability of these concepts to real-world flooding assessment. The results of this study are expected to be instrumental in improving the mitigation system, particularly for coastal areas in developing nations with similar ecological conditions.

Vulnerability is a critical aspect of disaster management, particularly in sustainable coastal management (Bang et al. 2019; Masselink & Lazarus 2019; Widianto & Damen 2014). This aspect comprises physical, socioeconomic, and environmental factors that increase a system's susceptibility

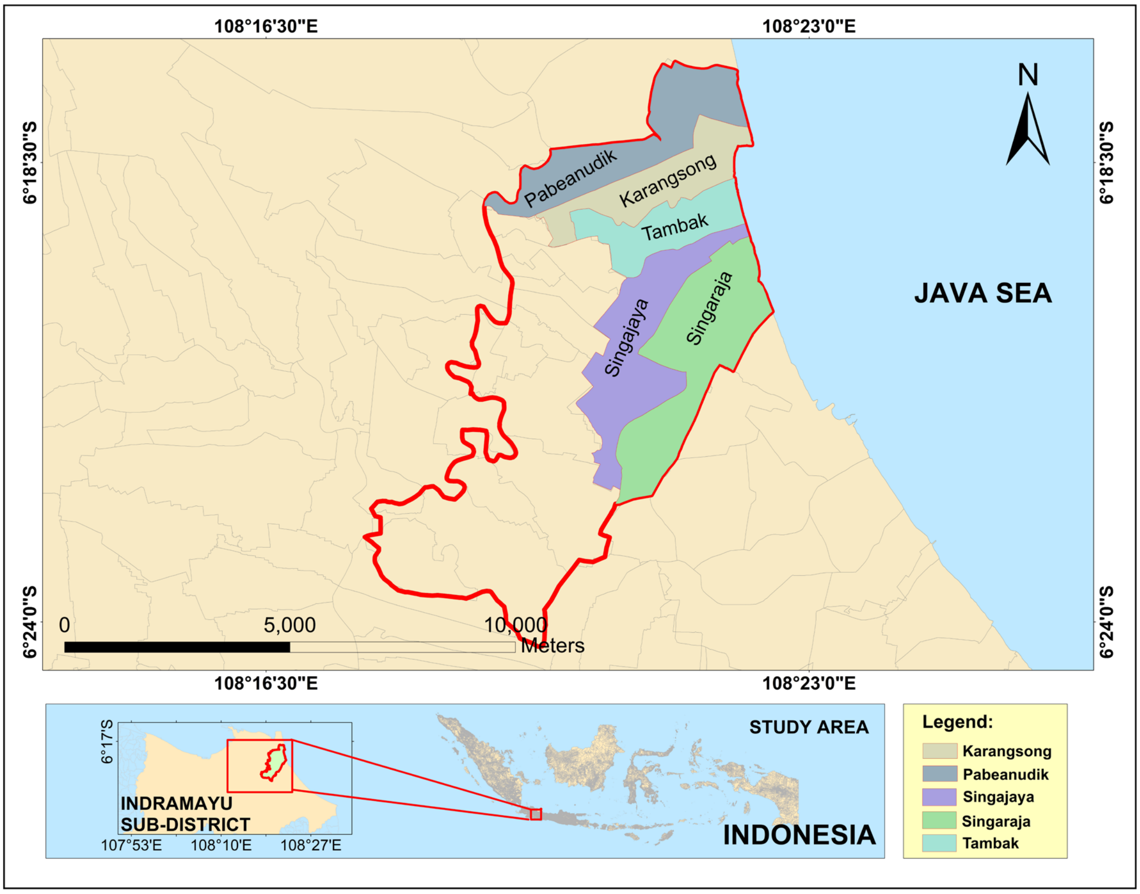


Figure 1. Five Coastal Villages in Indramayu sub-district, West Java, Indonesia. The maps were generated from Geospatial Information Agency, 2019)

to dangers, especially when adaptive capacity is dekcient (Adger, 1999; Cutter et al., 2003; Gathongo & Liem, 2019). The outcome of this vulnerability is the potential exposure to risk and knancial losses (Cutter, 2003). Furthermore, geographic Information System (GIS) methods have been reported to be effective techniques for analyzing vulnerability parameters for coastal risk assessment, allowing for comprehensive examination at various scales and providing valuable insights for decision-makers (Armaş & Gavris, 2013).

The study used Coastal Vulnerability Index (CVI) to identify physical vulnerability maps to tidal flooding and high waves (Bagdanaviiute et al., 2015; Marschiavelli et al., 2008). CVI measures coastal system susceptibility to environmental risk (Gornitz, 1991), while GIS methods, including satellite images, tidal tabular data, and geomorphology maps, are used to analyze vulnerability parameters for coastal risk assessment (Gornitz, 1991; Bagdanaviiute et al., 2015; Koroglu et al., 2019; Mohd et al., 2019; Mohamed, 2020; Sekovski et al., 2020).

CVI considers various factors, such as Geomorphological variables, including (Thieler & Hammar-Klose, 2000; Mohd et al., 2019), the historical shoreline change rate (V2); coastal slope (V3), and shoreline change rate (V2). These variables are typically used to evaluate a shoreline's relative resistance to erosion and accretion, long-term decline and accretion trend, and susceptibility to flooding, respectively (Pendleton et al., 2010). In this context, the wave energy driving the coastal sediment budget is represented by the mean signikcant wave height (V6), and the relative sea-level rise is presented as V4 (SLR). Tidal range, land cover, and mangrove zone width have been reported to be key factors in determining coastal vulnerability (Besset et al., 2019; Sekovski et al., 2020). Land cover, or V7, assesses inkltration characteristics from each land cover class (Sekovski et al., 2020), while V8 measures the width of mangrove zones, which aid in coastal resilience during high-energy events (Besset et al., 2019).

Based on the use of this index, areas at higher coastal risk can be identiked, leading to the prioritization of mitigation and adaptation measures. In this study, emphasis was placed on assessing the physical vulnerability of the study areas' coastlines to determine coastal behavior, identify the benekts and drawbacks of conditions caused by climate change, and evaluate potential risks from those conditions (Septriayadi & Hamhaber, 2013; Koroglu et al., 2019). CVI also enables regional comparisons and offers crucial data for coastal management and planning efforts. This study was carried out to help local authorities, decision-makers, and other stakeholders achieve sustainable risk mitigation, particularly for coastal areas.

Using this index, researchers can identify areas at higher risk of coastal hazards and prioritize them for mitigation and adaptation measures. In this study, we placed much emphasis on assessing the physical vulnerability of study areas' coastlines to determine coastal behaviour, to pinpoint the benefits and drawbacks of conditions brought on by climate change as well as potential risks from those conditions (Septriayadi & Hamhaber, 2013; Koroglu et al., 2019). The CVI also enables regional comparisons and offers crucial data for coastal management and planning efforts. Our research is aimed at helping local authorities, decision-makers, and other stakeholders achieve sustainable hazard mitigation, particularly for the coastal region.

2. Methods

Indramayu District in West Java, possessing distinct hydrometeorological conditions, comprised 5 coastal villages, including Pabeanudik, Karangsong, Tambak, Singajaya, and Singaraja, as shown in Figure 1. Furthermore, a combined pond area of 1810.28 ha was at risk of coastal disaster events, such as tidal flooding, which were introduced by regional winds, monsoons, and global phenomena (El Nino/La Nina and the Indian Ocean Dipole Mode), high tides, land subsidence, and sea level rise (Statistic Indonesia, 2018; Buchori et al., 2018; Setyawan & Pamungkas, 2017). The area also faced coastal erosion risk due to strong sea currents and storms, exacerbating the vulnerability of coastal villages and the inhabitants (Setyawan & Pamungkas, 2017). This led to the loss of valuable land and infrastructure. Mitigating the risk and protecting communities was crucial for sustainable development and well-being, in line with United Nations International Strategy for Disaster Reduction (2015) (Wallemacq et al., 2018).

Coastal Vulnerability Index (CVI)

A total of 8 variables were selected to assess CVI, as shown in Table 1. Furthermore, 6 of these parameters, including geomorphology (V1), coastal slope (V2), relative sea level (V3), shoreline change (V4), tidal range (V5), and signikcant wave height {V6}, were created by Thieler and Hammar-Klose in 2000 and used by Pendleton et al. (2010). Each land cover class was assigned a vulnerability score following the land cover (V7) parameter offered by Sekovski et al. (2020) based on the characteristics of inkltration, such as run-off potential. Furthermore, Ismail et al. (2012) and Besset et al. (2019) found that vegetation with a width of more than 100 m improved the resilience of coast to wave energy dissipation. The mangrove forest distance in this study was shorter than 200 and 300 m. These parameters were selected due to the importance in assessing coastal vulnerability and could effectively capture essential determinants of exposure.

This study used GIS methods to generate vulnerability parameters from satellite images, tidal tabular data, and a geomorphology map (Table 1). This approach helped investigate coastal risk at national, local, authority, and site levels. GIS methods were effective in analyzing vulnerability parameters for coastal risk assessment, providing valuable insights for decision-makers at different levels of authority (Mohamed, 2020).

A segment referred to in this study as a cross-shore transect with a length of approximately 1 km inland from shoreline was compared. Furthermore, there were 62 segments in total along the 6.12 km long coast of Indramayu, including 14, 15, 11, 3, and 19 segments in Pabeanudik, Karangsong, Tambak, Singajaya, and Singajaya, respectively. These segments knally

Table 1. The rank of each vulnerability parameter, following Thieler dan Hammar-Klose (2000); Pendleton et al. 2010; Besset et al. 2019; and Sekovski et al. 2020

Vulnerability Parameters	Physical Vulnerability Value				
	Very low	Low	Moderate	High	Very High
	1	2	3	4	5
Geomorphology (V1)	Rocky, cliffed coasts Fiords Fiards	Medium cliffs Indented coasts	Low cliffs Glacial drift Alluvial plains	Cobble beaches Estuary Lagoon	Barrier beaches Sand Beaches Salt marsh Mud flats Deltas Mangrove Coral reefs
Shoreline change (m/yr) (V2)	Accretion >2,0	Accretion 1.0 to 2.0	Stable -1.0 to +1.0	Erosion -1.1 to -2.0	Erosion <-2
Coastal Slope (%) (V3)	> 14.69	10.9 to 14.69	7.75 to 10.89	4.6 to 7.74	< 4.59
Relative sea-level (mm/yr) (V4)	≤1,8	1.8 to 2.5	2.5 to 3	3 to 3.4	>3.4
Mean tide range (m) (V5)	>6	4 to 6	2 to 4	1 to 2	<1
Wave height (m) (V6)	< 1.1	1.1 to 2.0	2.0 to 2.25	2.25 to 2.6	≥ 2.6
Land cover (V7)	Beaches and dunes, forests	Marsh	Agriculture	Barren soil	Built-up areas, water bodies
Mangrove width (m) (V8)	>1000	300-1000	100-300	<100	0

Table 2. Description of the collected data.

Vulnerability Parameters	Data type	Acquiring Date	Source of Data
Geomorphology (V1)	Geomorphology map (1:100.000)	2009	Centre for Geological Research and Development, Indonesia
Shoreline change (V2)	Sentinel 1A, Sentinel-2A; LANDSAT 5 TM; LANDSAT 7 ETM+; LANDSAT 8 OLI	2001; 2009; 2014; 2017; 2020	https://scihub.copernicus.eu
Coastal Slope (%) (V3)	SRTM 1 Arc-Second global	2014	tides.big.go.id/DEMNAS
Relative sea-level (mm/yr) (V4)	Tidal Tabular Data	2012	http://tides.big.go.id
Mean tidal range (V5) and significant wave height (V6)	Tidal Tabular Data	2010 to 2019	http://tides.big.go.id
Land cover (V7)	Sentinel-1A	2020	https://scihub.copernicus.eu
Mangrove width (V8)	Sentinel-2A; LANDSAT 5 TM; LANDSAT 7 ETM+; LANDSAT 8 OLI	2001; 2009; 2014; 2017; 2020	https://scihub.copernicus.eu

provided quantitative measurements that CVI evaluated based on each parameter.

An index was created, and the ranking scores for the individual cell measurements were very low (1), low (2), moderate (3), high (4), or very high (5) (Table 2). After the determination of ratings based on classikcation results, these values were calculated by dividing the total number of variables by the square root of the product of the ranked variables (Gornitz, 1991; Thieler & Hammar-Klose, 2000; Mohamed, 2020) as follows:

$$CVI = \sqrt[2]{\frac{V1\ x\ V2\ x\ V3\ x\ V4\ x\ V5\ x\ V6\ x\ V7\ x\ V8}{8}}$$

3. Result and Discussion

Geomorphology (V1)

The study area, which used a map scale of 1:100,000 and was made up of deltaic deposits and sandy beaches, contained (1) delta deposits (Qad), (2) coastal deposits (Qac) made up of sand fragments, sandy loam, and silt, (3) deposits from a young river (Qa), and (4) sandy beach (Qbr). Furthermore, sand beaches were specikcally vulnerable to erosion from waves and currents, making them more prone to flooding and inundation, as well as loss of valuable coastal land and infrastructure (Prawiradisastra, 2003; Mohamed, 2020). Local communities and ecosystems in these areas were at signikcant risk due to the increased susceptibility to flooding and inundation.

Shoreline Change (V2)

The results showed that erosion affected 29.87% of shoreline in 3 villages, namely Pabeanudik, Tambak, and Singaraja between 2001 and 2021. Pabeanudik shoreline experienced the highest rate of erosion, with an average rate of 18.1 m/year based on Thieler and Hammar (2000) Klose's ranking of coastal vulnerability (Table 3), which contributed to a very high rank of coastal vulnerability.

The results showed that shoreline dynamics along 5 coastal villages of Indramayu signikcantly influenced coastal risk, including tidal flooding and inundation, as shown in Table 3. In these areas, the dynamic changes in shoreline had increased vulnerability to environmental problem. Therefore, the local government must implement efkcient measures to reduce the risk and safeguard the local communities.

The Coastal Slope (V3)

National Digital Elevation Model (DEM) from Geospatial Information Agency of Indonesia was used to analyze various geographic features and terrain. DEM, created from sources, such as IFSAR, TERRASAR- X, and ALOS PALSAR, incorporated stereo-plotting Masspoint data and EGM2008 vertical datum. The slope values, computed in ArcGIS 10.3, showed the steepness of the terrain, aiding in understanding erosion, coastal vulnerability, and land use planning. Furthermore, the study area coastline was highly vulnerable, with 8.80% having a very high vulnerability. This flat coastline (47.23%) affected coastal pond flooding and aquaculture production. The high vulnerability and higher loss underscored the need for effective coastal management strategies to mitigate risk and protect aquaculture production in the area.

The relative Sea-Level Rise (SLR) (V4)

Based on the study by Kasim and Vincentius (2012), this study used the range of sea level rise (SLR), which was found to be 3,538–3,988 mm/year on average in Indramayu. According to Table 1, this relative SLR value was a signikcant factor in the high coastal physical vulnerability in the study area (Mohamed, 2020). The high value of coastal physical vulnerability showed that the site was at a greater risk of experiencing negative impacts from sea level rise.

Mean tidal range (V5) and significant wave height (V6)

The mean tidal range (V5) and signikcant wave height (V6) were determined using the tidal tabular data from Kejawan Cirebon tidal station (06° 44' 01.89" L South Latitude 108°35 '04.55" East Longitude). Furthermore, Monsoon activity in Indonesia from May to June caused a positive sea level anomaly and a high impact on "tidal flooding" due to semi-diurnal mixed tides with tidal ranges between 1.01 and 1.31 meters. This high tidal range drove the dynamic coastline change in the area, affecting the coastal sediment budget. The study areas had semi-diurnal mixed tides with tidal ranges between 1.01 and 1.31 meters, showing high vulnerability. This dynamic coastline change was driven by the high tidal range, while the signikcant wave height of 1.6 meters showed low vulnerability to inundation risk.

Land cover (V7) and mangrove width (V8)

Sekovski et al. (2019) found that inkltration impacted coast vulnerability to flooding, with kshponds being the primary income source in Indramayu, emphasizing the need for sustainable management strategies. This study analyzed land cover in 62 inland segments using Landsat 7 ETM+, Landsat 5 TM, Landsat 8 OLI, and Sentinel-2A data. The largest mangrove area in Pabeanudik Village was 11.15 ha in 2001.

Table 3. The rank of shoreline vulnerability

Village	The Rank Of Shoreline Vulnerability									
	Very low (1)		Low (2)		Moderate (3)		High (4)		Very High (5)	
	m/year	%	m/year	%	m/year	%	m/year	%	m/year	%
Pabeanudik	14.6	32.1	1.5	6.7	0	0	0	0	-18.1	61.2
Karangsong	18.5	100	0	0	0	0	0	0	0	0
Tambak	4.4	44.9	0	0	-0.2	22.9	-1.5	5.4	-3.1	26.7
Singajaya	0	0	0	0	1.1	100	0	0	0	0
Singaraja	4.5	19.2	1.4	18.7	-0.02	50	-1.9	6.04	-2.1	6.04

Note: Erosion (-); Akretion (+)

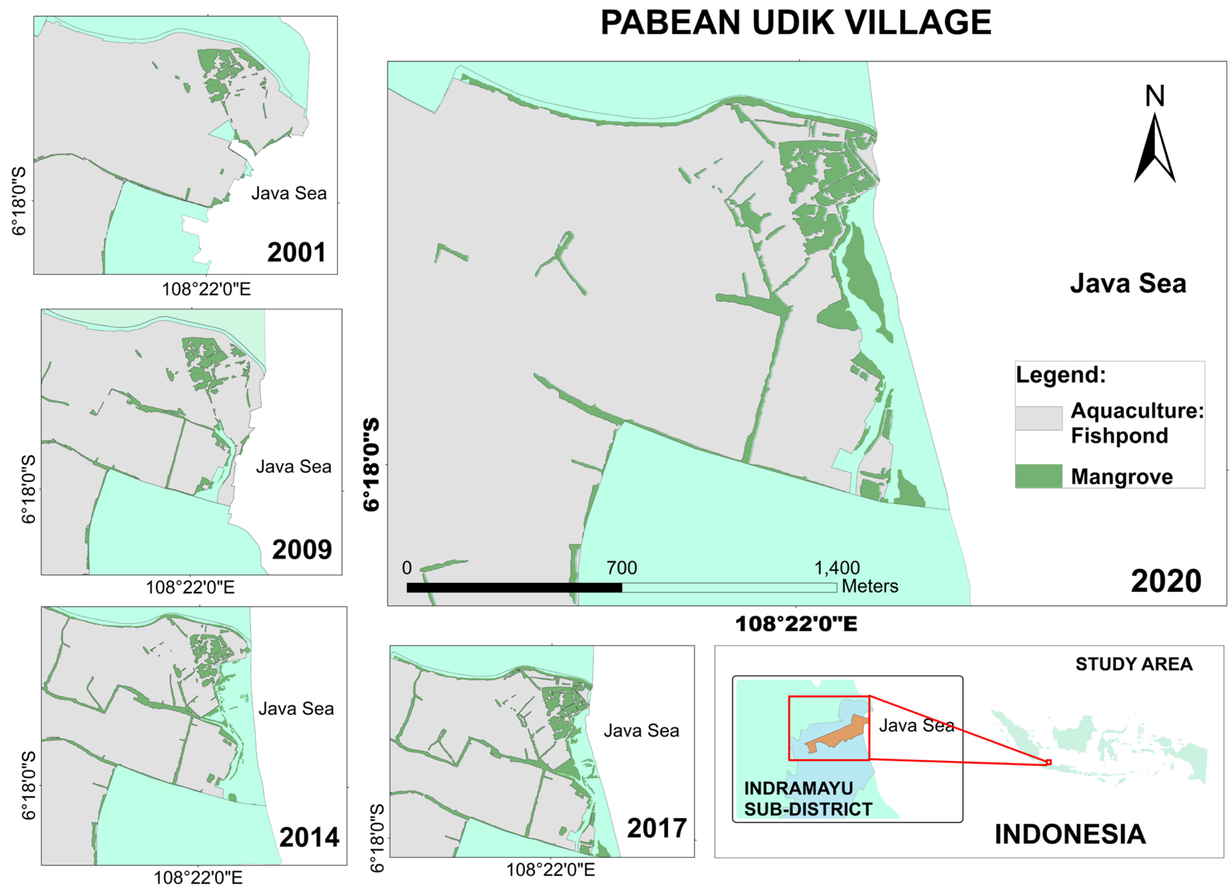


Figure 2. Area changes of mangrove forests (2001 to 2021) in Pabean Udik Village, Indramayu sub-district, West Java, Indonesia. The maps were generated form Landsat 5 TM, Landsat 7 ETM+, Landsat x-8 OLI dan Sentinel-2A, SRTM 1 Arc-Second global.

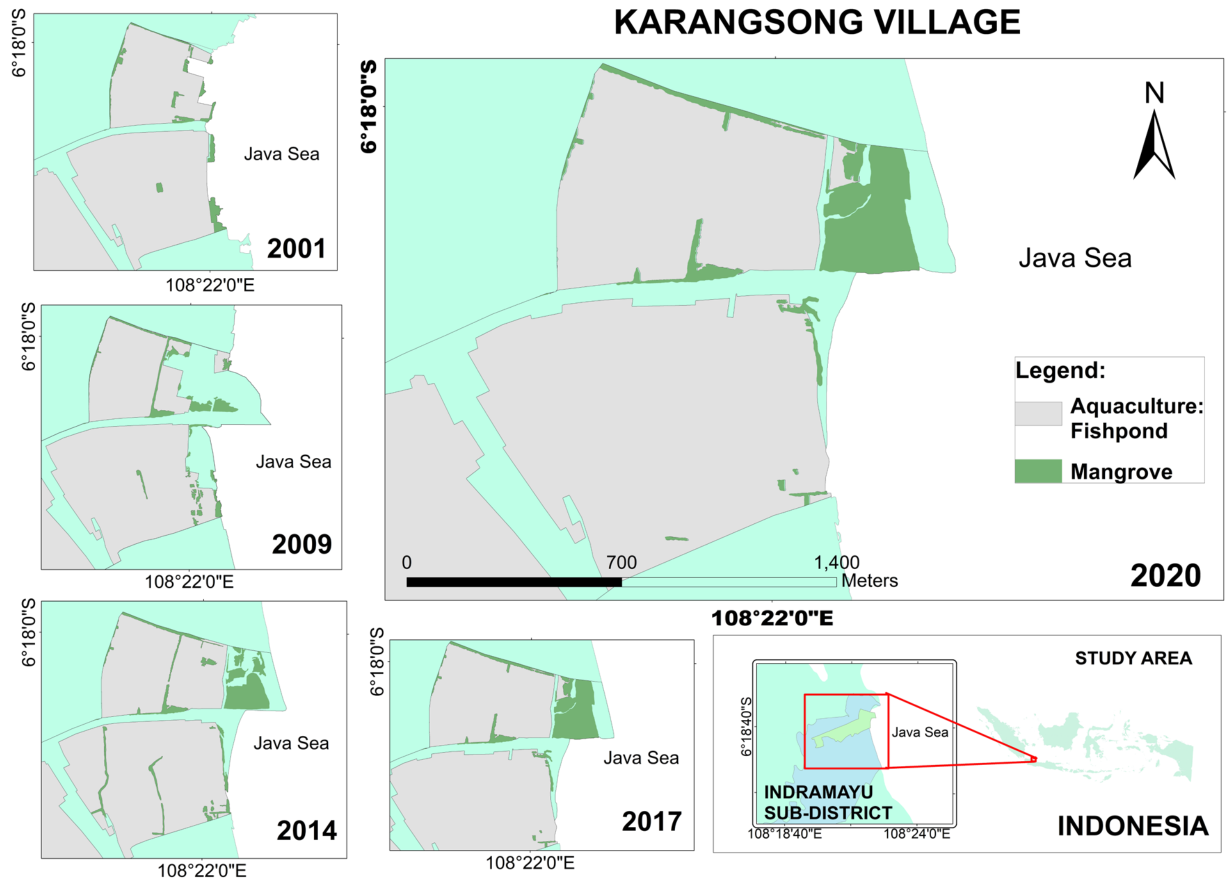
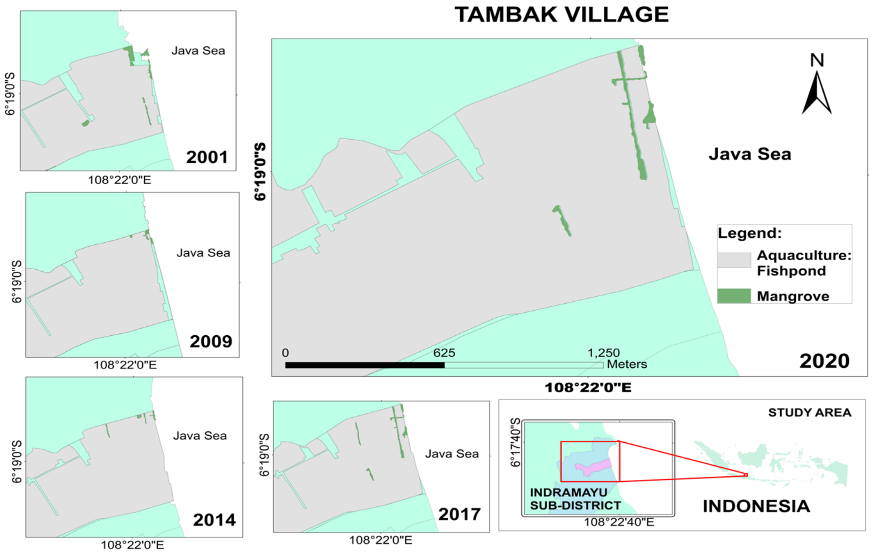
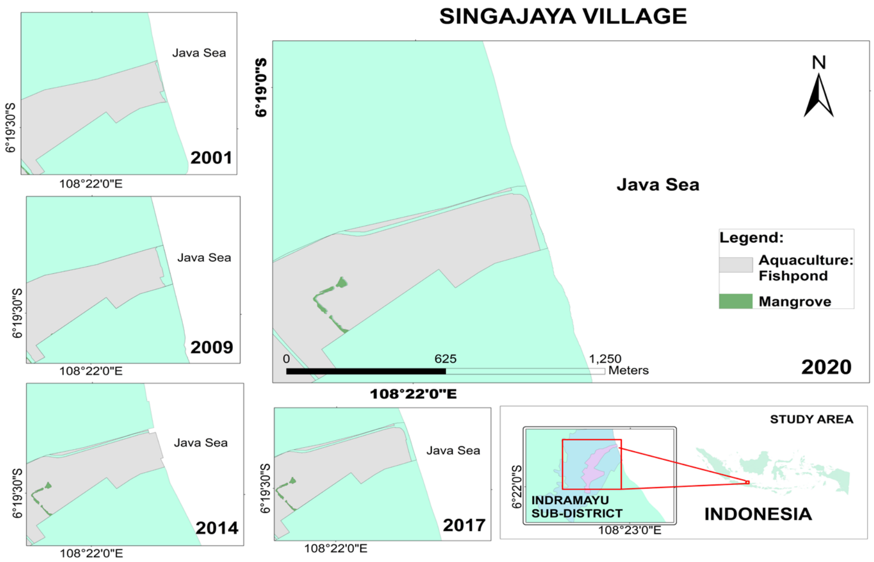


Figure 3. Area changes of mangrove forests (2001 to 2021) in Karangsong Village. The maps were generated form Landsat 5 TM, Landsat 7 ETM+, Landsat x-8 OLI dan Sentinel-2A, SRTM 1 Arc-Second global.



(a)



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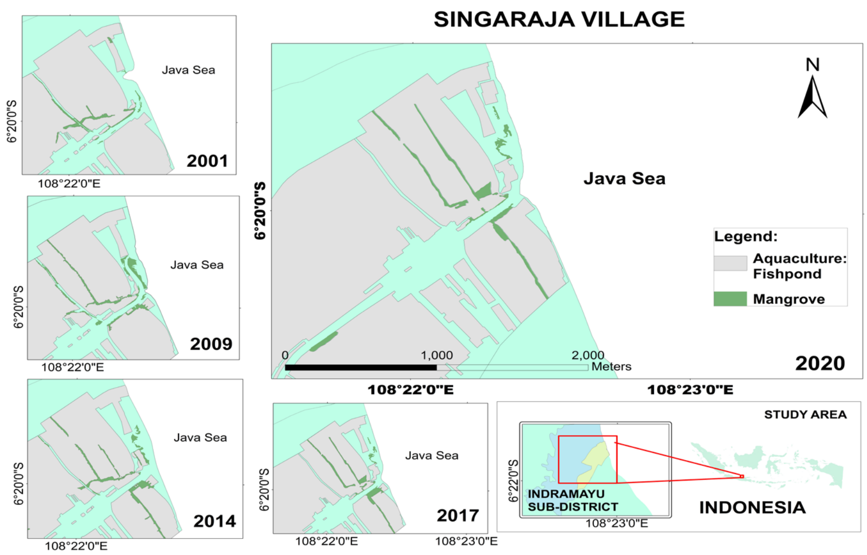
(b)



(c).

Figure 4. Area changes of mangrove forests (2001 to 2021). (a). Tambak Village; (b). Singajaya Village; (c). Singaraja Village. The maps were generated form Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI dan Sentinel-2A, SRTM 1 Arc-Second global.

The area experienced a signikcant growth of 90.3% in 2020, but the mangrove planting site on the seashore faced signikcant erosion due to tides, as shown in Figure 2 and Table 3.

Karangsong Village had a signikcant mangrove area of 5.08 ha, with signikcant growth of 177.76% until 2020 (Figure 3). Locals, government, and PT. Pertamina Reknery Unit IV had planted mangroves since 2008 to combat tidal flooding and coastal erosion. However, the area mangrove planting was concentrated on the north coast, causing coastal accretion and low vulnerability to tidal flooding. Tambak Village, with a 2.47 ha mangrove area, had a 33.6% degraded mangrove by 2020 (Figure 4a), causing low to high coastal vulnerability. The village ponds were highly vulnerable to tidal flooding due to the lack of mangrove areas. This showed that integrating mangrove restoration was crucial for addressing the local government tidal flooding.

Although there were smaller mangroves in Singajaya Willage than in Karangsong and Tambak, the area of

0.15 ha in 2001 (Figure 4b) increased by 160% by 2020. Tidal flooding that entered through the coast of this hamlet, similar to Tambak, was expected to affect the neighboring communities. Despite an increase of 72.27% in 2020, Singaraja village's 4.22 hectares still did not have many mangroves along shoreline. Therefore, coastal vulnerability results ranged signikcantly (Figure 4c), and it was still challenging to contain when tidal flooding deluge occurred.

Coastal vulnerability of Indramayu District

The vulnerability index in Indramayu coastal ranged from 5 to 86.60, with 4 categories, including low, moderate, high, and very high. This study divided vulnerability categories into 3 percentiles, with the 50th and 75th percentile values being 15.81, 22.36, and 35.35. 24.56% of the coastline was highly vulnerable to tidal flooding, followed by 22.13% with high vulnerability, 41.03% with medium exposure, and 12.28% with low levels (Figure 5).

Karangsong village's mangrove restoration reduced coastal vulnerability to tidal flooding by 22%, transforming it into an eco-tourism area and a beach protector. However, 25.33% and 52.67% of the village coastline remained highly vulnerable due to uneven terrain. Despite the restoration of mangroves as a natural barrier against flooding, 40.60% of Pabeanudik coastline remained moderately vulnerable. High coastal abrasion led to 26.56% and 26.32% of coastline being classiked as very high and high vulnerability (Figure 5). This study was in line with Li et al. (2014), suggesting spatial mapping of vulnerability assessments to reduce disaster impact on socio-ecological systems.

Table 4. The rank of Vulnerability in Indramayu District

The rank of Vulnerability in Indramayu District			
low	moderate	high	Very high
(1)	(2)	(3)	(4)
<5	5-15,80	15,81-22,35	>35,35

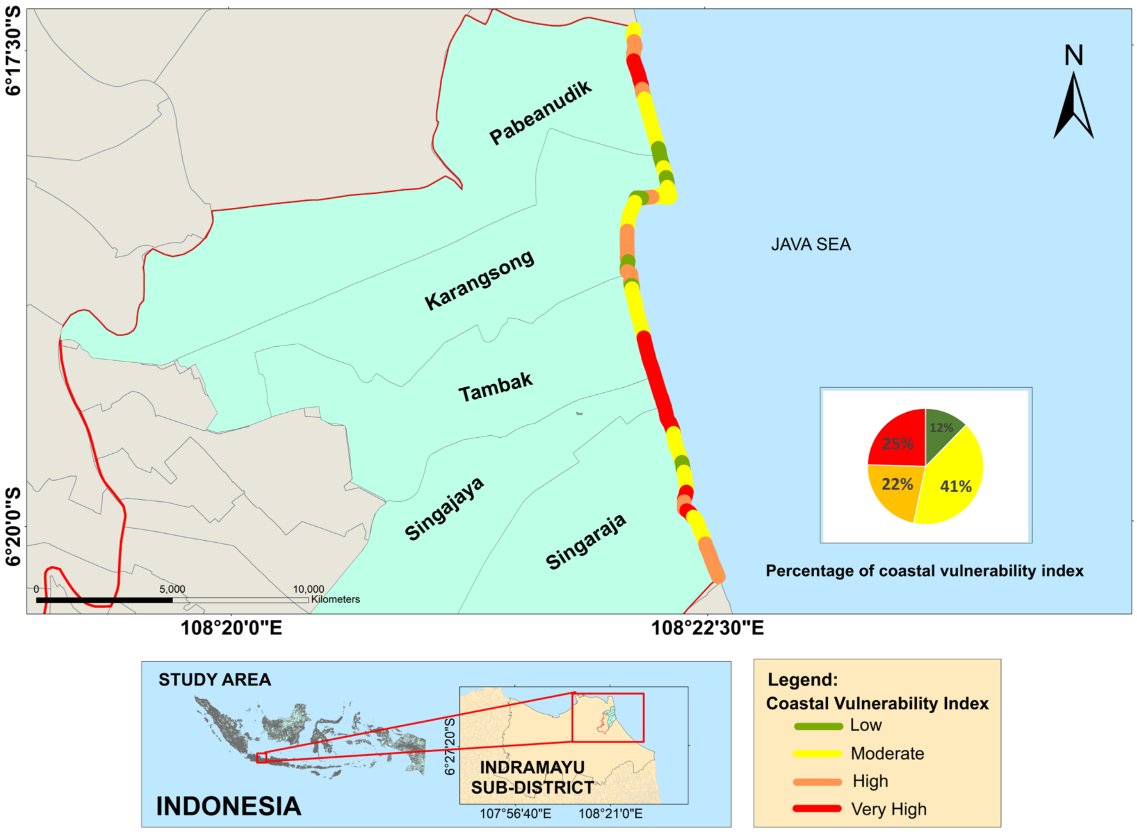


Figure 5. Coastal Vulnerability Map of Indramayu Sub-district Coast. The maps were generated form Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI dan Sentinel-2A, SRTM 1 Arc-Second global.

Tambak coastline exhibited high vulnerability to tidal flooding, with 16.67% classiked as vulnerable, as shown in Figure 5. The low mangrove area caused low inundation inkltration, leading to coastal abrasion. Tambak, Singajaya, and Singaraja were highly vulnerable to tidal flooding and waves. Singaraja coastline had a very high vulnerability (26.78%), 30.05% increased exposure, 38.8% moderate vulnerability, and 4.37% low vulnerability. The width of mangroves could protect against tidal flooding and reduce the impact of coastal disasters on the socio-ecological system, supporting the results of Besset et al. (2019) and Sekovski et al. (2020) that the parameters of mangrove land cover affected coastal vulnerability.

CVI in this study showed that only a few settlements in Indramayu could withstand tidal flooding. To reduce vulnerability and improve local farmers' income, the study recommended replicating mangrove restoration in Karangsong and enhancing coastal management using spatial data support, such as physical vulnerability zoning maps. This was consistent with the study of Li (2014) on the mitigation of coastal risk caused by tides and climate change. The results also supported Tyas et al. (2019) that the Komplangan silvokshery type was the best practice in the district. The Komplangan type of agroforestry comprised planting mangroves in front of ponds situated separately from the mangroves (Program for Indonesia by Wetlands International, 2005).

The results showed that only a few coastal communities in Indramayu could resist tidal flooding. This suggested that duplicating mangrove restoration in Karangsong and strengthening coastal management with spatial data support could lessen vulnerability and increase the revenue of neighborhood farmers. Furthermore, the results were in line with Tyas et al. (2019) recommendation of the Komplangan silvokshery type, which called for the planting of mangroves in front of various ponds. To maintain pond activities and build coastal resilience against tidal flooding and inundation, this study suggested mangrove restoration using the Komplangan silvokshery type 100 meters in front of the existing shoreline toward the sea (Figure 6).

4. Conclusion

In conclusion, this study analyzed 62 spatial datasets using remote sensing and GIS to assess the coastal vulnerability to tidal flooding in Indramayu. Furthermore, a comprehensive CVI was developed, integrating 8 physical parameters,

Figure 6. Recommendation for Rehabilitation/Restoration Mangrove in Indramayu. The maps were generated form Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI dan Sentinel-2A, SRTM 1 Arc-Second global.

as shown in Table 1. The results suggested that coastal infrastructure needed improvement to mitigate and adapt to long-term environmental changes. A total of 22.13% and 24.56% of shoreline in Indramayu coast range were considered high and very high vulnerability to tidal flooding. This study suggested that local governments should enhance policies to develop future mitigation strategies for disaster risk reduction, sustainable coastal management, and resilience. The results were consistent with Besset et al. (2019) and Ismail et al. (2000) that a minimum critical mangrove width of 100 m was sufficient for sea defense.

The results also contributed to existing literature on coastal vulnerability assessment in developing countries. Low-lying coastal plains, steep beach slopes, and a small mangrove area made Indramayu Regency the most vulnerable area to tidal flooding, according to the amended CVI evaluation. These areas had been made more vulnerable by human activities and changes in land cover. Tidal flooding could be reduced with targeted interventions, such as mangrove restoration and better land use planning. Other Indonesian coastal areas could also use the Komplangan method for mangrove restoration as a basis for adaptation measures.

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